
¹Based on observations obtained at the ESO VLT on Paranal, Chile, under programmes 63.I-0015 and 65.I-0135.

³As defined in Stolte et al. 2004 (Paper I), we refer to the central cluster in NGC 3603 as “NGC 3603 YC” to avoid confusion with the extended HII region.

The secrets of the nearest starburst cluster:

II. The present-day mass function in NGC 3603¹

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ABSTRACT

Based on deep VLT/ISAAC *JHK* photometry, we have derived the present-day mass function of the central starburst cluster NGC 3603 YC (Young Cluster)³ in the giant HII region NGC 3603. The effects of field contamination, individual reddening, and a possible binary contribution are investigated. The MF slopes resulting from the different methods are compared, and lead to a surprisingly consistent cluster MF with a slope of $\Gamma = -0.9 \pm 0.15$. Analyzing different radial annuli around the cluster core, no significant change in the slope of the MF is observed. However, mass segregation in the cluster is evidenced by the increasing depletion of the high-mass tail of the stellar mass distribution with increasing radius. We discuss the indications of mass segregation with respect to the changes observed in the binned and cumulative stellar mass functions, and argue that the cumulative function as well as the fraction of high- to low-mass stars provide better indicators for mass segregation than the MF slope alone. Finally, the observed mass function and starburst morphology of NGC 3603 YC is discussed in the context of massive local star-forming regions such as the Galactic Center Arches cluster, R 136/30 Dor in the LMC, and the Orion Trapezium cluster, all providing resolved templates for extragalactic star formation. Despite the similarity in the observed MF slopes, dynamical considerations suggest that the starburst clusters do not form gravitationally bound systems over a Hubble time. Both the environment (gravitational potential of the Milky Way) and the concentration of stars in the cluster core determine the dynamical stability of a dense star cluster, such that the long-term evolution of a starburst is not exclusively determined by the stellar evolution of its members, as frequently assumed for globular cluster systems.

Subject headings: HII regions: individual (NGC 3603) — open clusters and associations: individual (NGC 3603, HD 97950) — stars: pre-main-sequence — stars: mass

1. Introduction

High-mass star formation is still a puzzle to theorists and observers alike. Star-formation theory suggests that high-mass stars ($M > 20 M_{\odot}$) cannot form in the standard fragmentation and subsequent accretion scenario without serious modifications to the physical processes involved (Stahler et al. 2000). Competitive accretion (Bonnell et al. 2001), merging of protostellar clumps or young stars (Bonnell et al. 1998), and enhanced accretion in dependence on the star-forming environment (Behrend & Maeder 2001) are all scenarios suggested for the formation of O-type stars. All these processes share the requirement of exceptionally high gas and/or stellar densities to create high-mass stars.

The necessity of a high-density environment where altered physical processes shape the resultant stellar mass, and predominantly create high-mass stars at the cost of low- or intermediate mass objects, predicts primordial mass segregation in the densest star-forming loci, which might be evidenced in a flattened initial mass function (IMF) with a strong bias to high-mass stars in comparison to more moderate sites of star formation. In contrast to this, the IMF is found to be surprisingly invariant in a diversity of Milky Way and Magellanic Cloud star forming regions (Massey et al. 1995a, b).

The densest environments available to study the stellar mass spectrum are starburst clusters. In the Milky Way, only very few compact, dense starburst clusters are known, with the youngest and most condensed systems being the Arches clus-

ter close to the Galactic Center (GC) and the central starburst cluster in NGC 3603. These clusters are particularly important for our understanding of extragalactic star-forming regions, where the starburst mode is the predominantly observed mode of star formation due to the intrinsic brightness of compact, massive young clusters. Star-forming regions in other galaxies are, however, in most cases too distant to be resolved into individual stars. A detailed study of starburst clusters in the Milky Way provides a resolved template for extragalactic star-forming regions.

With the aim to observe possible deviations or to confirm the universality of the initial mass function in starburst environments, we derive the stellar mass distribution in NGC 3603 YC (Young Cluster). We analyze possible changes in the MF slope, in particular with respect to the distance from the cluster core, where the highest densities are found. A possible deviation from a standard MF in starburst environments would have severe consequences on our understanding of star formation in the nuclei and tidal interaction zones of distant galaxies, such as e.g. the Antennae galaxies, and star formation in the early universe when the star formation efficiency was more intense. This latter aspect refers not only to the distant universe, but also to the formation epoch of globular clusters in the Milky Way.

As the NGC 3603 YC starburst cluster is extreme among today's Milky Way massive star-forming regions, and with a stellar cluster mass of $\sim 10^4 M_{\odot}$ residing in a cloud of total gas mass $4 \cdot 10^5 M_{\odot}$ (Grabelsky et al. 1988) at the low-mass end of extragalactic starbursts, several at-

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tempts have been made to understand the stellar mass function. In all these studies, the resolution in the core was (and still is) the limiting factor, causing large uncertainties in the resultant MF shape. From optical photometry, Mof-fat et al. (1994) obtained a MF slope of $\Gamma = -1.4 \pm 0.6$ for $30 < M < 60 M_{\odot}$, i.e., the 77 brightest stars. Hofmann et al. (1995) derived $\Gamma = -1.6$ in the mass range $15 < M < 50 M_{\odot}$ from only 28 central stars resolved with speckle interferometry. While these slopes are consistent with a Salpeter MF, only the massive stellar population is traced. The limitations in resolution additionally constrain these results mostly to the outer cluster regions (except for the speckle data, where statistics are very poor). The earliest attempt towards a complete central MF was performed by Eisenhauer et al. (1998), who derived a MF slope of $\Gamma = -0.73$ for $1 < M < 85 M_{\odot}$ in the innermost $13''$ of the cluster center from ESO/ADONIS high-resolution adaptive optics photometry. In this study, crowding effects were taken into account via spatially varying incompleteness ratios, and the presumed age spread of $0.3 - 1$ Myr on the PMS was considered by calculating a median age of the young, intermediate mass population of 0.5 Myr from individual positions of PMS stars in the color-magnitude diagram. Although these authors give strong arguments for a young main-sequence cluster age of only $1 - 2$ Myr, they use a 3 Myr Geneva isochrone to derive the MF at the high-mass end. Recently, Sagar et al. (2001) confirm this slope with $\Gamma = -0.84$, however from ill-resolved *UBVRI* data, such that, again, the innermost cluster region could not be traced. Despite these uncertainties

in previous studies, high-resolution *VRI* HST/PC data ($\text{FWHM} < 0''.1$) yield a similarly flat slope of $\Gamma = -0.9 \pm 0.1$ in the mass range $1 < M < 100 M_{\odot, \text{initial}}$ in the inner $20''$ of the cluster center using a composite isochrone for the MS and PMS population with a single age of 1 Myr (Sung & Bessell 2004).

We will use the cluster characteristics determined in Stolte et al. 2004 (hereafter Paper I, where we give a detailed introduction on NGC 3603; see also the introduction in Sung & Bessel 2004 for a review on the cluster), in particular a uniform cluster age of 1 Myr and a distance of 6 kpc (Paper I), to derive mass functions and possible radial variations in the MF from VLT/ISAAC near-infrared data (see Paper I, and Brandl et al. 1999) obtained under excellent seeing conditions ($\text{FWHM} < 0''.4$). This data set contains the deepest currently available photometry of NGC 3603 YC, allowing one to observe cluster members down to masses of $\sim 0.1 M_{\odot}$, well into the subsolar regime.

In Sec. 2, we give a brief summary of the observations presented in Paper I. The use of high-resolution near-infrared data allows us to derive the MF slope down to $0.4 M_{\odot}$ in the crowding-limited cluster field, while at the same time minimizing effects from variable extinction. We recall the critical cluster properties used in the MF derivation in Sec. 3 from Paper I. The mass functions are derived in Sec. 4, and the resultant slopes are discussed in Sec. 5. Radial variations in the MF slope are analyzed in Sec. 6, and the effects of mass segregation are interpreted in Sec. 7. Because of the impact of mass segregation on our understanding of the star formation pro-

cess, we present a detailed comparison between different star-forming environments in Sec. 8. Finally, we summarise our main results briefly in Sec. 9.

2. Observations

A detailed analysis of the photometry of NGC3603 YC is presented in Stolte et al. (2004, Paper I), where color-magnitude and color-color distributions of the cluster center were derived and discussed. For the sake of completeness, a brief summary of the observations contributing to the derivation of the mass function is given here. Deep VLT/ISAAC observations were taken in the J_s , H , and K_s bands. The J_s and K_s observations resulted in the best resolution due to stable observing conditions, while the seeing degraded and varied during the H -band observations. The J_s and K_s data display the highest spatial resolution on the final images, thus yielding the best photometric performance, and will therefore form the basis for the mass function derivation. In order to avoid artefacts and nebulous peaks, it was nevertheless required that each object in the final photometric catalogue be detected in all three filters, including H .

With the goal to resolve the cluster center, two sets of images were created. As crowding (as opposed to photometric depth) is the most limiting factor in the cluster center, the lowest seeing images were combined to J_s and K_s integrations of 9 and 11 min, respectively, covering a $2' \times 2'$ field of view centered on the cluster. The final resolution on the combined images is $0.''38$ in J_s and $0.''35$ in K_s . In addition, the total set of 35 images in J_s and 39 images in K_s yielded combined frames

of 35 and 39 min exposure time and a field of view of $3'4 \times 3'4$, with final resolutions of $0.''40$ and $0.''37$, respectively. This larger field is used to estimate the field contamination in the cluster sample from the edge of the field of view, where crowding does not affect the photometry. The brightest stars in the field and in particular the bright core of NGC 3603 YC inside a radius of $R = 7''$ suffer from severe saturation, such that the core itself had to be excluded from the analysis. As the most massive stars reside inside the core, this implies that the upper end of the mass function cannot be derived from these data. As no NIR data set with comparable resolution covering the larger cluster area is available at the present time, we cannot easily fill in the high-mass end. Analysis of the upper end of the mass function in the cluster core as determined from high-resolution adaptive optics or HST/WFPC2 data is discussed elsewhere (Eisenhauer et al. 1998; Sung & Bessell 2004), and the results from these studies will be included in the discussion of the mass function.

The details of the observations can be found in Paper I, Sec. 2, Tabs. 1 and 2.

3. Cluster properties of NGC3603 YC

In Sec. 4, various methods will be used to derive the mass function in NGC 3603 YC. Before the methods suggested from the complex physical properties observed in the cluster center are described (cf. Paper I), the main physical parameters such as the distance, the age and the metallicity of NGC 3603 YC are recalled from Paper I.

3.1. Distance, extinction and age derived from the PMS transition region

The distance, extinction and age of the starburst cluster were determined from the ISAAC data via isochrone fitting to the pre-main sequence/main sequence (PMS/MS) transition region in Paper I. Palla & Stahler (1999) pre-main sequence isochrones of ages 0.3-3 Myr were used to perform the fit. The selection of isochrones is discussed in Paper I. As these parameters are crucial for the mass function derivation, we summarise the results below.

3.1.1. Distance to NGC 3603

Kinematic distance estimates to NGC 3603 YC range from 6 to 10 kpc, while early photometric studies yielded $\sim 7 \pm 0.5$ kpc (Moffat 1983; Melnick et al. 1989). The purely empirical distance of 7 kpc derived by Moffat (1983) from optical photometry and spectral classification of massive cluster members was essentially used in all subsequent studies. Although independent of stellar evolution models, these early photometric distance determinations were restricted to the main sequence population.

We obtain a distance modulus of $DM = 13.9 \pm 0.1$ mag from isochrone fitting of the PMS/MS transition region. The corresponding distance, $d = 6 \pm 0.3$ kpc, is slightly lower than previously derived values, but consistent with the kinematic distance estimate of 6.1 ± 0.6 kpc from De Pree et al. (1999), and the photometric distance of 6.3 ± 0.6 kpc derived by Pandey et al. (2000).

3.1.2. Foreground extinction to NGC 3603

The foreground extinction as derived from spectra of high-mass stars close to the cluster center is $A_V = 4.5 \pm 0.3$ mag (Moffat 1983), and $A_V = 4.6 \pm 0.6$ from optical photometry (Melnick et al. 1989). Melnick et al. 1989 observe a radial extinction variation, confirmed by Pandey et al. 2000, which suggests an extinction of 4 mag ($E_{B-V} \sim 1.3$, albeit uncertain due to large scatter) when extrapolated to the cluster center¹.

A foreground extinction of $A_V = 4.5 \pm 0.6$ mag is derived from PMS isochrone fitting towards the pre-main sequence population in Paper I, consistent with earlier studies. The large uncertainty mirrors the low sensitivity of infrared observations to granular material along the line of sight. This choice also fits the lower PMS stars towards fainter magnitudes, beyond the distinct, horizontal transition region. A slightly lower extinction of $A_V = 4$ mag is derived for main sequence stars, pre-dominantly found close to the cluster core, slightly lower than extinction estimates from spectroscopic studies, where values around $A_V = 4.5$ mag were suggested (Moffat 1983), but consistent with the core extinction expected from the radial trend observed by Melnick et al. 1989. In this estimate the assumption was made that the resolved secondary sequence is comprised of a physically distinct popula-

¹A radial variation may be an oversimplification, especially because IRAS maps indicate a North-South orientation of dense material around the cluster (Nürnberg et al. 2002). The insensitivity of NIR data prohibits a more accurate determination of the spatial extinction variation.

tion (due to binarity or other physical processes), and therefore excluded from the isochrone fit. Objects on the secondary sequence display redder colors, such that the extinction estimate increases when the whole population is considered, in agreement with earlier results.² As stars will be dereddened individually in the MF derivation, which implies shifting stars along the reddening path to $A_V = 0$ mag, the difference in extinction between PMS and MS is meaningless for the mass calculation.

3.1.3. Age of the starburst cluster

The age of NGC 3603 YC has evolved in the literature during the past 20 years. Early studies suggested an age of 2-3 Myr from the fact that presumably evolved stars with strong winds and Wolf-Rayet characteristics reside in the cluster center (Moffat 1983). In the past decade, however, it became increasingly clear that extremely massive stars of type O2 show strong Wolf-Rayet characteristics while still on the main sequence (see, e.g., Walborn et al. 2002). A main sequence nature is evidenced in the spectra of the most massive stars in NGC 3603 YC by strong hydrogen emission (Drissen et al. 1995; Drissen 1999). Moffat et al. (2002) argue that the WR stars in NGC 3603 YC are “probably main sequence stars of extremely high luminosity with strong wind-produced emission lines” from the cor-

relation observed between X-ray and radio flux, which is uncorrelated for normal Galactic (single) WRs. Massey & Hunter (1998) compare the spectra of three WRs in NGC 3603 YC to similar stars observed in R 136/30 Dor, and conclude that these are probably “super O stars”. From the short main sequence lifetime of these massive beasts, the estimated cluster age has decreased in the literature to about 1 Myr (Drissen 1999; Moffat et al. 2002), which is consistent with age estimates indicated by PMS isochrones (Brandl et al. 1999; Eisenhauer et al. 1998).

In Paper I, we obtain an age of 1 Myr as the best fit to the PMS/MS transition region. The significant width of the transition region caused the suggestion of an age spread between 0.3 and 1 Myr in the starburst cluster in these previous studies. As discussed in detail in Paper I, there are two straight-forward interpretations of the width of the transition region. In addition to an age spread, the PMS transition can also be interpreted as comprised of a mixture of single and binary stars, with the well-populated upper envelope indicating binaries with mass ratios close to unity. This interpretation is supported by a secondary sequence observed close to the main sequence in the ISAAC data. From χ^2 distance minimisation, the best fit to the PMS population is obtained for a single cluster age of 1 Myr, including the assumption that stars on the secondary sequence are binaries. An age distribution can, however, not be entirely excluded prior to a detailed spectral analysis of objects in this regime. For the mass function derivation, we will therefore assume a single cluster age of 1 Myr, while treating the secondary

²Note, however, that increasing color terms for redder PMS stars could not be taken account due to the limited number of standard stars. Thus, we cannot entirely rule out an instrumental color effect between MS and PMS, or uncertainties in the extinction law or PMS isochrones, to cause the derived deviation in A_V . See Paper I for a detailed discussion of the uncertainties.

sequence in different ways to minimise a potential bias introduced by the interpretation of the secondary sequence, e.g. as binaries.

As stars on the MS do not evolve severely, slight deviations in the age determination are not critical for the derivation of the main sequence MF ($M > 4 M_{\odot}$ according to a 1 Myr Palla & Stahler (1999) isochrone). At these young ages, stellar evolution is almost negligible except for the highest mass objects, which are not included here, such that the mass function derived from a 1 Myr MS isochrone should not deviate significantly from earlier MFs using a 3 Myr model. The main sequence portion of the MFs derived in the following is therefore comparable to the results of previous studies, while the pre-main sequence MF depends strongly on the assumed age and the treatment of stars in the transition region.

The isochrones used to determine masses of individual stars from the color-magnitude plane will be shown along with the PMS and MS selection of stars in Sec. 4, Fig. 5 (see also Paper I).

3.1.4. *Metallicity of NGC 3603*

No thorough analysis of NGC 3603 with respect to metallicity is available in the literature. The spectral analysis of the WR-like massive component in the cluster core suggests a metallicity close or equal to solar (Schmutz & Drissen 1999). NGC 3603 is located at a Galactocentric distance of 8 kpc, comparable to the Sun. The radial gradient in metallicity observed in the Milky Way supports that the metallicity in NGC 3603 is comparable to the solar value, which was adopted.

3.2. **Uncertainties in the mass function derivation**

The color and brightness of stars at the youngest evolutionary stages are influenced by a diversity of processes. Variable extinction can be caused by circumstellar envelopes or a variation in the density of remnant molecular material along the line of sight. Near-infrared excess emission from circumstellar disks alters the colors and increases the apparent reddening of stars, thereby causing an overestimate in the stellar mass of individually dereddened objects with intrinsic NIR excesses. Binarity/multiplicity increases the brightness, again resulting in an overestimate of the stellar mass. The large scatter observed in particular at fainter magnitudes in the PMS/MS transition and PMS region of the CMD suggests that these evolutionary stages are especially affected, although the increasing photometric uncertainty toward fainter magnitudes prohibits a quantitative analysis of increasing NIR excesses in PMS vs. MS stars. These uncertainties for masses below $4 M_{\odot}$ have to be kept in mind during the derivation and interpretation of mass functions.

While variable extinction can be taken into account by individually dereddening stars to the theoretical isochrone, NIR excess and binarity are difficult to assess. As the majority of stars in NGC 3603 YC are found close to the fitted isochrone, severely reddened sources, either excess cluster members or background objects, can be excluded from the MF derivation without significant statistical loss. Multiplicity can usually not be taken into account in MF derivations. With the interpretation of the secondary sequence in NGC 3603 YC

as a sequence of binaries with mass ratios close to unity, we can, however, estimate the contribution of (equal-mass) binaries to the MF and correct for this effect.

4. The Mass Function in the central NGC 3603 cluster

4.1. General remarks on the mass function derivation in NGC 3603 YC

As a consequence of the clear separation of a pre-main sequence and a main sequence population observed in the central CMD of NGC 3603 YC, and the existence of a visible secondary sequence interpreted as binary candidates (see Paper I), the mass function derivation has to incorporate a number of physical assumptions. While generally one favourite set of stellar evolution models is chosen to derive the mass function via isochrone fitting, in the case of NGC 3603 YC two different sets of evolutionary models are required to represent the MS and the PMS population at a given age. As the 1 Myr pre-main sequence isochrone from the Palla & Stahler set of models fits both the transition of the PMS to the MS as well as the lower PMS distribution best (cf. Paper I), this isochrone is chosen for the transformation of luminosities into masses on the PMS. For the evidence given above and in Paper I, the MS population is also consistent with a single star-forming burst 1 Myr ago. Along with the binary interpretation, this suggests a single age for the entire cluster population, without the need to employ an age spread. The mass-luminosity relation for main sequence stars is deduced from a 1 Myr solar metallicity isochrone from the Geneva basic grid of stellar evo-

lution models (Lejeune & Schaerer 2001). Effects such as enhanced mass loss are not taken into account, as the ISAAC data are saturated for stars with masses above $20 M_{\odot}$, below which mass loss is not significant at these young ages. In addition, the case of a 2 and 3 Myr MS isochrone, used in prior MF derivations and allowing for some uncertainty in the derived age, will also be tested to deduce potential effects of stellar evolution on the resulting MF slope.

The identification of a secondary sequence poses an additional challenge to a realistic MF derivation. As no prior data set of the starburst cluster resolved this feature clearly, the MF will be shown with and without binary correction to allow comparison with prior MF derivations.

As a consequence of the variable extinction observed in the NGC 3603 region, individual dereddening was applied to determine stellar masses. As the NIR data alone do not allow us to derive the extinction law toward NGC 3603, the extinction law was adopted from Rieke & Lebofsky (1985). Each star has been shifted along the reddening vector in the J_s , $J_s - K_s$ plane onto the PMS or MS isochrone. Although this procedure is more accurate in the sense that individual reddening is taken into account, it implicitly assumes that all scatter observed in the CMD is caused by reddening variation. This is clearly not the case. Besides the photometric scatter inherent in the data, other processes such as binarity, stellar rotation, and intrinsic IR excesses contribute to the scatter. Most of the additional processes influencing a very young stellar population are difficult to quantify, and cannot be taken into account in the following analysis. While photometric un-

certainties are expected to introduce random scatter, such that their combined effect should be negligible, individual dereddening allows one to estimate the maximum influence of extinction variations on the MF slope. The intense crowding in the cluster center decreases the detectability of lower-mass stars and can cause a systematic uncertainty in the MF slope, which would mimic a bias to high-mass stars. For each cluster area/annulus the average incompleteness is therefore estimated as a function of the radial distance from the cluster center and hence stellar density.

While a detailed analysis of the uncertainty in the MF slope imposed by the choice of stellar evolutionary models is beyond the scope of this paper, a thorough discussion on this subject can be found in Andersen (2004).

The procedures used to derive the stellar mass distribution in NGC 3603 YC are outlined in detail in the next sections.

4.2. Incompleteness correction

Artificial star tests were performed on each science frame to determine the recovery fraction per magnitude. Between 200 and 250 stars were inserted in each artificial frame to avoid enhancing crowding effects. 45 artificial frames were created from the smaller $2' \times 2'$ “cluster” images and 30 artificial frames from the larger $3.4' \times 3.4'$ “field” images. The inserted number of stars corresponds to less than 1% of the total number of stars detected on each image. Magnitudes and positions were assigned randomly using the *addstar* task in IRAF. As the cluster itself covered only a small area on the high-resolution frames, additional simulations were performed on

the innermost $60'' \times 60''$, with 100 to 150 artificial stars or $\leq 2\%$ of the stellar population found in the cluster center. Source detection and PSF fitting was conducted with the same parameters as for the stellar photometry. The procedure was repeated to yield the recovery fractions for ~ 6000 stars in the field frames, and ~ 11000 stars in total on the cluster frames, with 6000 stars distributed randomly over the entire image, and 5000 stars confined to the critical central region. The resultant recovery fractions were applied in two steps during the analysis: 1) during field star correction and 2) during incompleteness correction of the mass function.

4.3. Field star correction

The field star fraction was derived from an area to the North and East of the cluster center. This region is particularly well suited to estimate field stars in the low-extinction cluster center, as it is neither influenced by strong HII region emission nor shows evidence of variable or enhanced extinction. Field stars were statistically subtracted in each 0.5×0.5 mag color-magnitude bin of the CMD. Prior to statistical field star subtraction, the number of field stars had to be corrected for the varying stellar density (crowding) with radial distance from the cluster center. For this purpose, the field and cluster recovery fractions, f_{field} and $f_{cluster}$, were fitted as a function of the magnitude as a third order polynomial as displayed in Fig. 3. The number of field stars is corrected for field incompleteness as $n_{field,corr} = n_{field}/f_{field}$, i.e. to a field completeness of 100%. This number was then reduced according to the expected recovery fraction of

stars in the radial annulus studied, yielding a combined correction of $n_{field,final} = f_{cluster} \cdot n_{field,corr} = f_{cluster}/f_{field} \cdot n_{field}$, with $f_{field,final} = f_{cluster}/f_{field}$ corresponds to the final density/crowding correction factor applied to adjust the field star number counts to the cluster center. In addition, the measured number of field stars on the larger field area was scaled down to the cluster or annulus area considered.

The incompleteness simulations yielded independent correction factors for each filter. In principle, the combined probability to find a field star in each color-magnitude bin in the J_s , $J_s - K_s$ plane is then given by the product of the individual probabilities, $f_{JK} = f_J \cdot f_K$. In the color and magnitude range covered by the cluster center stars, however, the incompleteness is entirely determined by the J -band limit. Thus, only J -band incompleteness is taken into account in the mass function derivation. The correction factor f_J for each magnitude is obtained from the polynomial fit. The measured number of field stars is corrected by the factor derived for each annulus studied, and the adjusted number of field stars is then statistically removed from the cluster CMD.

As the extent of the cluster is debated, with estimates ranging up to a radius of 2.5 (Nürnberg & Petr-Gotzens 2002), the area covered by the ISAAC data may overestimate the field star contamination. As the low-mass halo surrounding NGC 3603 YC is mainly composed of faint, low-mass stars, the bright central cluster population should not be severely affected³.

³Ideally, a separated field should be used to estimate the background population. One off-field

Fig. 4 shows the effects of field subtraction on the central cluster population, and also indicates the 50% completeness limit for this radial selection, down to which mass function slopes will be derived.

In the following sections, the different approaches used to derive the mass function in NGC 3603 YC will be described in detail. Results for all MF derivations are summarised in Tab. 2. The combined PMS/MS mass functions of this selection are fitted in Fig. 6. The apparent MS population fainter than $J_s = 15.5$ mag, corresponding to the 1 Myr MS turn-on at $\sim 4 M_\odot$, is likely comprised of MS stars in the NGC 3603 region. This population has to be far older than the cluster age, and cannot originate in the cluster. The lower MS beyond the cluster MS turn-on is therefore excluded from the fit. Thus, the combined low-mass MF below the MS turn-on at $M = 4 M_\odot$ is solely comprised of PMS stars.

4.4. Simple star counts

In the simplest model, the luminosity of a star reflects its evolutionary stage and mass. This ignores all processes changing the luminosity and thus magnitude of a star individually and independently of its evolutionary stage. The isochrone can then be applied directly to each given stellar magnitude to transform the brightness distribution into a mass function. As this

was observed at a distance of $\sim 30'$ from the cluster center, but unfortunately turned out to contain a different stellar population dominated by older giant stars. The strong spatial variations in the stellar population along the Carina arm complicate the determination of the field star contribution in any particular region.

is the most frequently used method to derive mass functions, we include it here as the simplest approach. Field data are not always available, and field contribution can indeed be negligible in the dense cluster regions, such that field star contamination has rarely been taken into account in MF derivations of the NGC 3603 YC (except for the study of the cluster center by Eisenhauer et al. 1998). In order to show the effects of field contamination alone, MFs were calculated from simple star counts both with and without field subtraction.

4.5. Individual dereddening

The stellar population in NGC 3603 shows individually varying extinction, caused either by variations in the distribution of granular material in the foreground, or by individual reddening from remnant circumstellar envelopes. The maximum possible effect of individual reddening on the MF slope can be probed by assuming that the photometric scatter is caused by varying extinction alone. Individual reddening is then taken into account via dereddening each star along the reddening vector (Rieke & Lebofsky 1985) in the $J_s, J_s - K_s$ plane until an intersection with the corresponding isochrone is reached, and the mass of the star is determined from the intersection point. The extinction applied to the isochrone itself is not relevant in this case, as only the length of the dereddening path (i.e., the relative shift in the CMD) depends on the location of the isochrone, but not the desired intersection point. For the MF derivations below, isochrones matching the average foreground extinction of the MS and PMS

populations were used, and stars blueward and redward of the isochrone have been shifted accordingly. The blue and red limits in the distance from the isochrone was determined by eye from the stellar distribution in the $J_s, J_s - K_s$ plane. As the main sequence is not affected by field star contamination, all stars around the MS are included in the MF, with a color selection of -0.25 mag blueward and +0.35 mag redward of the MS isochrone. The bulk of the PMS population, where reddening is more severe, can be included selecting colors -0.25 mag blueward and +0.5 mag redward of the PMS isochrone. This rejects the reddest objects ($A_V > 7.5$ mag), which might be affected by infrared excesses and background contamination. The selection of stars contributing to the mass function is shown in Fig. 5.

Note that most of the stars are found in a very narrow range around the PMS, in an envelope of only -0.1 to +0.15 mag. This narrower selection does not alter the slope of the PMS MF alone, but in comparison with the MS MF too few stars are found in the transition region, such that MS and PMS do not agree at the transition mass. Therefore, the wider PMS selection was used, resulting in very good agreement of the MS and PMS MF bins at the transition mass.

In all following MF derivations, field subtraction and individual reddening are taken into account.

4.6. Treatment of the PMS/MS transition region

Stars in the transition region between PMS and MS were allocated PMS transi-

tion masses, which are in the narrow range between 2.5 and $4 M_{\odot}$, depending on their distance to the isochrone. No individual dereddening was performed in this case due to the large scatter in the transition region. There is a slight ambiguity in the Palla & Stahler isochrone in the sense that stars with 3.5 to $4 M_{\odot}$ cannot be distinguished, but this is not relevant for the resultant MF as these stars all fall into the same mass bin. Only masses above the hydrogen burning turn-on of $4 M_{\odot}$ enter the MS MF. Although this facilitates the analysis as a clear cut is introduced between MS and PMS contributions, the transition region is clearly physically more complex than envisioned in this simple treatment. In particular, stars contributing to the MS may be scattered away from the narrow range beyond the PMS transition point in the CMD, rendering the respective MS and PMS contributions close to the $4 M_{\odot}$ PMS limit very uncertain. The transition mass will be marked in all derived MFs, such that the combination of MS and PMS contributions is clear, and in particular the last PMS and first MS bin should be observed with care.

4.7. Treatment of the secondary sequence

Evidence for a binary nature of a secondary sequence observed in the ISAAC CMD of NGC 3603 YC is given in Paper I. However, this interpretation is as yet unproven by spectroscopy. Three different approaches are therefore chosen in the treatment of the secondary sequence. 1) The secondary sequence is completely rejected from the mass function derivation. As the relative fraction of stars on the sec-

ondary sequence is not observed to vary with stellar brightness within the statistical uncertainties, removing stars on the secondary sequence corresponds to statistically subtracting $\sim 30\%$ of the population above $2.5 M_{\odot}$, below which the vertical turn of the PMS does not allow one to distinguish a secondary sequence. While this may result in too low star counts in high-mass bins with respect to the low-mass MF, the statistical properties and thus the slope in the high-mass MF should not be altered. 2) The distinct interpretation is ignored and the entire population is used for the MF derivation, in agreement with earlier studies. This MF is also directly comparable with MF derivations that do not have the photometric accuracy or resolution to attempt a binary correction, such as the early study by Salpeter (1955). 3) The binary interpretation is used to correct for the effect of binaries with mass ratios close to unity on the resultant MF slope.

4.7.1. Binary rejection

The selection of stars on the secondary sequence was shown and carefully discussed in Paper I, see esp. Fig. 7. The band of stars above the transition region and redward of the main sequence was rejected in the first estimate of the MF, assuming that some currently unknown physical process causes the offset in the CMD, and thus masses may not be accurately determined. If stars on this sequence are not subject to a mass bias from a different formation process, the resultant “single” mass function should represent the underlying statistically-unbiased stellar population of

the star cluster. The vertical distribution of lower PMS stars does not allow such a selection. Even if the same photometric offset is included in the case of PMS stars, as is to be expected from the secondary sequence extending all the way into the transition region, such an offset is invisible in the vertical PMS feature. As a consequence, the corresponding PMS stars cannot be rejected, and only the MS and the transition region (down to $2.5 M_{\odot}$) are affected by binary rejection.

4.7.2. *Binary correction - MS and transition region*

As a first step toward a binary corrected MF, the visible binary candidate sequence above the main sequence and the transition population was adjusted. The J_s -band magnitude of the selected stars was increased by 0.75 mag as expected for equal-mass binaries, and an additional companion star with equal color and magnitude was included in the number counts. This procedure makes the simplifying assumption that all binaries contributing to the brighter secondary sequence are close to equal-mass systems as suggested from the observed magnitude offset, in accordance with the observational restriction that for arbitrary mass ratios no prediction can be made. Thus, the MFs derived below are still system MFs uncorrected for companions with masses significantly lower than the primary mass. The adjustment is applied after field subtraction, before individual dereddening and MF calculation. This way, the bias from individual dereddening of equal-mass binaries due to the larger brightness and thus higher mass estimate is avoided. The resultant pairs of “single”

stars are treated in exactly the same way as the rest of the population.

4.7.3. *Binary correction - statistical PMS correction*

While a secondary sequence is observed above the MS and the PMS transition region, the problem of the merging of binaries into the lower PMS population remains. The fraction of stars observed on the secondary sequence is approximately 30% of the total number of stars both parallel to the MS and in the PMS/MS transition region ($J \leq 15.5$ mag). When intervals of 1 mag width are studied, no trend is observed (Tab. 1) toward fainter stars. Thus, to correct for the equal-mass binary contribution on the PMS a constant binary fraction of 30% has been assumed. If no binary formation mechanism enhances the number of high-mass binaries or decreases the number of low-mass binaries with mass ratios close to unity, a significant fraction of binaries should be hidden in the PMS distribution. In order to correct for the bias imposed on the derived MF, 30% of the PMS stars were selected randomly, shifted down by +0.75 mag and an additional companion was added, as in the case of the MS binary sequence. If the equal-mass binary fraction is the same for each mass bin, as suggested from the MS and transition region, this procedure should statistically correct for the overestimate of individual masses due to brighter magnitudes of potential binaries.

5. **Discussion of the resultant mass functions**

Mass functions were created from the above procedures with a histogram bin

width of $\log(M/M_\odot) = 0.2$, starting at $0.1 M_\odot$. A linear least-squares fit was applied to the incompleteness corrected MF from the 50% completeness limit all the way to the highest mass bin. At the high-mass end of the MS MF, saturation losses thin out the CMD. As a consequence of the combination of different exposures taken under varying conditions, the saturation limit is not a sharp point, but extends over a range of ~ 1 mag in J_s . The approximate fraction of stars lost due to saturation in the upper mass bin, $M < 20 M_\odot$, is $\sim 50\%$. The high-mass end of the MF has been corrected accordingly, and is included in the MF fit. The MF in NGC 3603 YC is consistent with a single-slope power law over the entire mass range probed by our data, $0.4 < M < 20 M_\odot$. Note that the apparent turn-over below $0.4 M_\odot$ is not included in the fit, and we are not able to draw conclusions on the possible turn-over mass in NGC 3603 YC, because the MF is heavily depleted by incompleteness, and the correction increasingly uncertain.

All resultant MF slopes are summarised in Tab. 2 and sample MFs are shown in Fig. 6. The derived individual slopes of the MS alone (see Fig. 6 and Tab. 2) are meant to illustrate effects of the different corrections introduced, and should not be taken at face value due to the low number of bins included in these fits. The PMS isochrone covers a large range in color over a narrow mass range in the transition region where PMS stars equilibrate to main sequence hydrogen burning. The colors in the transition region range from $J - K = 0.7$ mag to $J - K = 1.3$ mag with masses between 2.5 and $4 M_\odot$. Only four model points are available for the transition region, such

that the mass transformation had to rely on interpolation between theoretically predicted color, magnitude and thus mass values. This is likely the cause for the enhancement of stars seen in each MF in the mass bin centered on $2 M_\odot$, and the subsequent depletion in the number of stars in the following mass bin centered on $3.2 M_\odot$. The combined MS/PMS mass function is less affected by the two subsequent bins at PMS/MS transition masses, such that the continuous mass function yields the most reliable fit.

After the effort undertaken to correct for the effects discussed above, the derived mass function slopes show remarkably small scatter. A few general tendencies are observed. First of all, the slope of the PMS MF is very stable with values ranging from $\Gamma = -0.61$ to -0.85 , with a scatter smaller than the formal least-squares fitting error of ~ 0.25 . The MS MF is more severely affected by binary correction than the PMS MF. This is expected as the upper mass bins are emptied without substitution from higher mass bins due to the saturation truncation, while binary intermediate- and low-mass stars are replenished from brighter bins. As the upper end of the MF is heavily affected by saturation, the loss in stars and resultant steepening of the MF is a consequence of saturating the *binary* sequence.

The slope of the combined mass function is not considerably affected by the MS variations, but shows remarkable consistency with values ranging from -0.84 to -0.99 with a formal fitting error of ± 0.1 . As expected for the core region with $R < 1$ pc, field contamination has only a minor effect on the MF slope (Tab. 2, cf. Fig. 2).

The use of an older main sequence of 2 or 3 Myr does not change the combined MF fit significantly (see Tab. 2), as expected⁴. The most reliable derivation of the mass function in the central cluster area of NGC 3603 YC including all corrections discussed in the previous sections is displayed in the bottom panel of Fig. 6. The slope of the mass function including field subtraction, individual dereddening and binary correction is $\Gamma = -0.91 \pm 0.08$ over the mass range $0.4 < M < 20 M_{\odot}$.

A slope of $\Gamma = -0.77$ down to $M > 1 M_{\odot}$ was derived by Eisenhauer et al. (1998) from high-resolution ADONIS data in the innermost $13''$ of the cluster center, in reasonable agreement with our estimate. These authors did not account for binaries, and interpreted the observed scatter in the PMS/MS transition as an age spread in the range 0.3 to 1 Myr. Accordingly, a mean age of 0.5 Myr was used to derive masses of PMS stars. As shown in Paper I, Fig. 4, this interpretation is consistent with the data as long as the photometric accuracy does not allow one to resolve the equal-mass binary offset. A younger age and thus evolutionary state results in assigning lower masses to the stars. Comparably, binarity correction results in assigning stars with a given brightness a (well-defined) lower mass. As the 0.3 Myr isochrone coincides well with the binary sequence, the masses on the PMS derived for the transition stars are comparable. On the other

hand, the effect of possible companions on the MF is not taken into account in the case of an age spread. Statistically adding companions at a constant fraction in all magnitude bins should, however, not alter the MF slope. Thus a comparable slope in the MF using a younger isochrone for the transformation of magnitudes into masses as opposed to binary correction can be understood from the similarity of the 0.3 Myr and the binary isochrone.

A severe difference between both data sets remains, limiting the above comparison. Mass segregation in the cluster, in the sense that massive stars may be found predominantly in the cluster center as observed in the case of the Arches cluster (Stolte 2003), would cause the MF slope to steepen with increasing radius. As the ISAAC data are limited to $R > 7''$ due to saturation, while the ADONIS data only extend out to $R < 13''$, a steeper MF would be expected from ISAAC than from the central ADONIS data in the presence of mass segregation. The comparison is complicated by the different procedures used. When the MF is calculated with mere field subtraction, without dereddening and binary correction for a 1 Myr isochrone, the slope becomes $\Gamma = -0.86$, slightly, but not significantly steeper than the ADONIS slope. No significant change can be found between the ADONIS core MF and the ISAAC MF outside the core. This agreement is even more surprising as the core is known to be mass segregated within $R < 6''$ from HST/WFPC2 data (Sung & Bessell 2004). Sung & Bessell derive a MF slope on the HST/PC area of $40'' \times 40''$ ($R \lesssim 20''$) of $\Gamma = -0.9 \pm 0.1$ in the *initial* mass range $1 < M < 100 M_{\odot}$.

⁴Note that for the PMS only the best-fitting model was used, while other models and ages unable to reproduce the stellar population in the CMD are not considered (see Andersen 2004 for a discussion on MF slope variations as a function of PMS models).

This slope agrees surprisingly well with our slope using present-day masses. Stellar evolution at these young ages only becomes significant for stars in excess of $\sim 50 M_{\odot}$, such that the mass range of $0.1 < M < 20 M_{\odot}$ covered by our ISAAC data is not influenced by post-main sequence evolution. The correspondence in both MFs might be a cause of the consistent age estimate of a 1 Myr single-age starburst in both derivations, but the consistency is still surprising in view of the different procedures and evolutionary models applied. In summary, the integrated MF slope in NGC 3603 YC is with -0.9 slightly flattened with respect to a Salpeter slope, $\Gamma = -1.35$, suggesting the efficient formation of high-mass stars in the cluster center, but not a strong deviation from a normal IMF.

6. Radial variation in the mass function of NGC 3603 YC

Radial mass functions were derived including field subtraction, individual dereddening and correction for binaries on the MS as well as on the PMS as described above. Three annuli covering equal areas were selected, each covering $1/3$ of the area enclosed within $7'' < R < 33''$. The smallest accessible radius of $7''$ is determined by saturation in the cluster core. The radial selections correspond to $7'' < R < 20''$, $20'' < R < 27''$, and $27'' < R < 33''$ (cf. Fig. 1). The mass functions for these annuli are shown in Fig. 7.

The slopes of the MFs displayed in Fig. 7 in the innermost two annuli agree roughly within the uncertainties, and only a marginal increase from -0.9 ± 0.15 ($7 < R < 20''$) to -1.1 ± 0.15 ($20 < R < 27''$) is

observed. Sung & Bessel (2004) observe an increase from $\Gamma = -0.5 \pm 0.1$ in the cluster core ($R < 6''$) to -0.8 ± 0.2 for $6 < R < 12''$ and -1.2 ± 0.2 for $12 < R < 20''$, suggesting that mass segregation is most pronounced in the core and the MF steepens to normal values rapidly beyond the core radius, in good agreement with our values for Γ taking into account the different radial selections applied. In the outermost annulus, $27 < R < 33''$, the MS is almost entirely depleted, and a reasonable power law fit can only be applied to the PMS. The PMS fit yields $\Gamma = -0.8 \pm 0.2$, such that a further systematic increase in the slope at larger radii is not supported by our data.

Despite the comparable slopes in all annuli, the truncation and depletion of high-mass stars yields strong evidence for mass segregation in NGC 3603 YC. This indicates that the slope alone is not adequate to describe mass segregation processes. While the low-mass (PMS) distribution decreases in number as the density decreases with larger radial distance, the shape in each annulus shows a close resemblance. The high-mass (main sequence) end on the other hand becomes more and more depleted with increasing radius. From the incompleteness corrected number counts, we can estimate whether the MS depletion is consistent with the expected decrease in stellar density as observed for the PMS. While the cluster center ($7'' < R < 20''$) harbors ~ 250 PMS stars, the PMS population in the second annulus decreases to ~ 87 or 35% of the central population. In the third annulus, 72 PMS stars remain, indicating a slow decrease in the density of low-/intermediate-

mass stars. The MS population harbors 78 high-mass stars in the innermost annulus. With the same decrease in stellar density, 27 MS stars are expected in the second annulus, while only 17 are observed, and 23 should still be present in the third annulus, where only 4 (!) MS stars are found. We can conclude that the depletion on the MS is much stronger than expected from the decrease in stellar density with increasing distance from the cluster center, providing strong evidence for segregation of massive stars inside the cluster core.

In stark contrast to the strong outwards variation in the MS population, the shape of the PMS distribution of stars remains similar throughout all annuli. The truncation at very low masses in the first and second annulus is due to crowding losses of faint stars, as indicated by the incompleteness correction. As the lowest mass bins are incomplete by more than 90%, a final conclusion on a possible change in the low-mass population can only be drawn for stars more massive than $1 M_{\odot}$, where the completeness fraction is more than 50% in all annuli. No significant change is observed in the 3 mass bins above this threshold. The 50% limit progresses down to $0.4 M_{\odot}$ in the two outer annuli, where no strong variation in the MF is observed between both these annuli. Even when the analysis is extended to radii of $65''$, well outside the distinct cluster center, the field subtracted MF displays the same slope in the PMS regime (see Tab. 3). The relative fraction of stars detected down to the lowest mass included in the Palla & Stahler models, $0.1 M_{\odot}$, increases noticeably in the outermost annulus. Taking into account the incompleteness correction in

all annuli, a truncation in the mass function of NGC 3603 YC at the low-mass end can safely be ruled out down to $0.4 M_{\odot}$.

7. Mass segregation in NGC 3603 YC

As the slope of the combined MS+PMS mass function does not vary significantly with radial distance from the cluster center, this measure cannot be used to draw conclusions on mass segregation in NGC 3603 YC. From the mass functions, there is strong evidence that the PMS population alone, covering a mass range of $0.4 < M < 4 M_{\odot}$ from the 50% completeness limit to the PMS/MS transition, is not segregated. There is no indication of a flattening or depletion of the MF at the low-mass end towards the cluster center. Nevertheless, the truncation of high-mass MS stars with $M > 4 M_{\odot}$ beyond a radius of $27''$ is a clear indication of mass segregation in the massive population. Such a behaviour can be expected from primordial mass segregation assuming that high-mass stars form predominantly in the densest cluster region, and may thus have resided close to the cluster center throughout their lifetime, while low-mass stars can form anywhere inside the parental cloud. However, dynamical segregation will also transport high-mass stars inwards and low-mass stars outwards during interactions.

Although in a cluster as young as ~ 1 Myr a location of massive stars in the cluster center is very suggestive of primordial segregation, Bonnell & Davies (1998) derive a similar stellar distribution from N-body simulations of dynamical cluster evolution. For their richest cluster with 1500 stars statistically drawn from a combined Salpeter (1955) and Kroupa et

al. (1990) MF truncated at $m_{low} = 0.1 M_{\odot}$, and a standard number density profile, $n \propto r^{-2}$, 90% of the massive stars migrate into the innermost 0.5 half-mass radii within 10 crossing times, no matter whether the massive stars were originally randomly distributed in the cluster potential or concentrated near the half-mass radius. Independently of the exact segregation timescale, these models thus also yield strong evidence that initial conditions are lost rapidly. Although we cannot derive the core radius and in particular the crucial contribution of the massive component in the core to the cluster potential from the ISAAC data, a core radius of ~ 0.2 pc is estimated from HST/WFPC2 observations (Grebel et al., private communication). Furthermore, a velocity dispersion of a few km/s is typically observed in dense clusters. This core radius leads to a crossing time of only 10^5 yr in the case of a velocity dispersion of 2 km/s. According to Bonnell & Davies, heavy mass segregation should have created a high-mass dominated cluster core after $10t_{cross}$ or in our example only 1 Myr. This order of magnitude estimate suggests that the segregation timescale expected from cluster evolution models is comparable to the cluster age, and thus that the cluster was already shaped by heavy dynamical segregation. This early loss of initial conditions prohibits conclusions on the formation locus of high-mass stars. We can therefore not distinguish primordial from dynamical segregation in NGC 3603 YC from the present-day distribution of high-mass stars.

To derive more quantitative conclusions on the mass segregation in NGC 3603 YC,

two other means are investigated in the following sections. First, cumulative functions were created from the mass distribution to avoid the binning dependence inherent to the standard MF derivation. Secondly, the number ratio of high-mass to low-mass stars is analyzed as a function of the radius.

7.1. Cumulative Functions

Cumulative functions (CFs) are created by consecutively adding stars with decreasing mass, starting with one star at the highest mass observed. The field-subtracted, color-selected distribution of stars used to derive the mass functions enters the cumulative functions. Masses are assigned to individual stars during individual dereddening in the same way as for the MF derivation. The only difference to the mass distributions in the MFs is that the artificially added companion stars for binary correction are not counted as stars in the CF. These “stars” have not been observed as individual sources, and the correction is - in particular on the PMS - purely statistical. As the only indication for binaries is given by the binary candidate sequence observed in the higher mass population, only equal-mass binaries can be taken into account. Systems with smaller mass ratios cannot be distinguished from single stars. If the binary stars are not biased to a certain mass range, the mass distribution in binary stars is the same as in single objects. Adding companion stars thus adds to the total mass, but not to the statistical properties of the distribution. The brightness correction of 0.75 mag for stars on the secondary sequence, however, is crucial, as $\sim 30\%$ of

the individual masses are overestimated if the brightness is indeed enhanced in these stars (by binarity or other physical mechanisms). Thus, the CFs are created from all stars selected as cluster members in the CMD after field-subtraction, with masses corrected for the derived binary fraction of 30%.

The resultant cumulative functions of the central cluster population as well as the radial variations in the CFs are shown in Fig. 8. Theoretical CFs corresponding to a single exponent power-law MF are underlaid for exponents of $-0.3 > \Gamma > -1.3$. For the main cluster area, $7'' < R < 33''$, the main sequence stars in the mass range $4 < M < 12 M_{\odot}$ follow closely the $\Gamma = -0.7$ line. The irregular shape at higher masses is partially due to random sampling of the upper MF as well as saturation losses for $M > 15 M_{\odot}$. Between 3 and $4 M_{\odot}$, the irregularity arises in the ambiguity of stellar locations in the CMD and thus individual masses in the PMS/MS transition region. The pre-main sequence distribution favours a flatter value of $\Gamma \sim -0.5$.

In the cluster center ($R < 20''$), the CF tangents the $\Gamma = -0.3$ curve for $M < 2 M_{\odot}$, and Γ tends to -0.5 at higher masses. At larger radii, the CF falls towards steeper values of Γ as expected in the case of mass segregation. On the PMS, however, this effect is weak, and the general shape of the CF remains remarkably constant out to radii where almost no main sequence stars remain. This is particularly pronounced in Fig. 9, where the PMS region below $3 M_{\odot}$ can hardly be distinguished in all annuli except for the slightly flatter CF in the cluster center. This supports the finding of Nürnberger &

Petr-Gotzens (2002) of a cluster extent of $R \sim 150''$ beyond the edges of our field of view. This pre-main sequence population can be interpreted as an extended halo of low-mass stars comparable to the halo observed around the Trapezium in the Orion Nebula Cluster (Hillenbrand 1997).

The situation at the high-mass end is very different. For stars with masses $M > 2 M_{\odot}$, the CF in the outer annuli indicates increasingly steeper values of $\Gamma \sim -0.7$ to -0.9 . At larger radii, the high-mass end becomes increasingly depleted, evidenced in a steep decline of the CF toward higher masses. The most striking feature in the main sequence population is the sharp truncation of the CF at $\sim 2.5 M_{\odot}$ for radii $R > 27''$. This cut-off corresponds to the absence of main sequence stars in the mass functions (cf. Fig. 7), and indicates that massive stars are highly segregated toward the cluster center. Beyond $33''$, the irregular CF shape and increase in the scaled frequency of high-mass stars, obvious in Fig. 9, marks the onset of field contamination, as at large radii statistics of cluster stars become poorer and realistic field subtraction more difficult than in the dense cluster center where cluster members dominate.

From these cumulative distributions, we see that binning effects influence the slope of the mass functions significantly, and the assumption of a single exponent power-law distribution is over-simplified. While the MF concept is useful as a tool to compare results from different data sets and regions, yielding a single characteristic value, the assumptions entering such analyses have to be carefully reviewed before conclusions on “universality” or “deviation” from a cer-

tain mass distribution are drawn.

7.2. Fraction of high- to low-mass stars

The fraction of high-mass main sequence stars to low-mass pre-main sequence stars, $f(\text{high/low}) = n(> 4 M_{\odot})/n(< 4 M_{\odot})$, is derived as a function of distance from the cluster center. Individual mass derivations for stars in each separate annulus are used including field-star and incompleteness corrections for each radial selection. In addition, the cluster population within $7'' < R < 33''$, yielding better statistics than the outer annuli, is split into $5''$ bins in steps of $2''.5$ to allow a more complete radial coverage. The MS/PMS transition mass, $M = 4 M_{\odot}$, as the natural mass separation in the stellar population of NGC 3603 YC is chosen to distinguish high- and low mass stars. Consequently, the fraction of high- to low-mass stars also reflects the fraction of MS to PMS stars.

A strong decrease in the fraction of massive vs. low-mass stars is seen in Fig. 10. While 44 % of all stars with $M > 1 M_{\odot}$ in the cluster core, $7'' < R < 10''$, have masses above $4 M_{\odot}$ (and $M < 20 M_{\odot}$), this fraction drops to 20 % already at a radius of $20''$. At a radius of $33''$, the contribution of massive stars is below 5 %. Beyond this radius, field contamination at the bright end skews the ratios again towards higher values. The steep decrease reflects the high-density concentration of massive stars in the cluster center, while at larger radii, $R > 30''$, the cluster is dominated by the extended low-mass population.

An even steeper drop is observed in the *mass fraction* of high- vs. low-mass stars (right panel in Fig. 10). While the total

mass in high-mass stars exceeds the low-mass contribution by a factor of 1.8 close to the cluster center, meaning that high-mass stars contribute 64 % to the total mass, the ratio of the mass in high- vs. low-mass stars drops to 0.2 at $R = 33''$, such that high-mass stars contribute only ~ 17 % of the total mass at large radii while dominating the mass in the cluster core. Note that in this estimate, the compact, massive core of the starburst is excluded due to saturation. The flat core MF ($\Gamma = -0.5$) derived by Sung & Bessel (2004) for radii $R < 6''$ indicates a strong bias to high-mass stars in the core, such that including the massive core population would enhance the percentage of mass contributed by high-mass stars in the center of NGC 3603 YC.

As can be seen in Fig. 10, these variations in the number and mass fractions with radius are a very efficient tool to quantify mass segregation effects.

8. From Orion to R 136 - a structural comparison

Starburst clusters as massive and compact as NGC 3603 YC are rare in our close neighborhood. In the Milky Way, only the Arches cluster close to the Galactic Center is known to have comparable mass and density (Stolte 2003). Clark et al. 2005 argue that the recently unveiled Westerlund 1 cluster is comparable to Arches in core density and might have a total mass of $10^5 M_{\odot}$ under the assumption of a normal IMF, but only the most massive stars down to type B0 are analysed so far, while the low-mass population is as yet unknown. In the literature, NGC 3603 is extensively compared to the massive 30 Doradus star-forming complex in the Large Magellanic

Cloud (LMC), hosting the dense cluster surrounding the compact, star-like source R 136, which features a core density derived from O and WR stars comparable to the central NGC 3603 starburst cluster (e.g., Moffat 1994). With a total mass of $2 \cdot 10^4 M_{\odot}$, the central cluster around R 136 in 30 Dor is at the upper mass end of local young star clusters, and at the same time at the low-mass end of Milky Way globular clusters. The large distance of 6 and 8 kpc to NGC 3603 YC and Arches, respectively, allow only limited study of their low-mass population. This limitation applies to R 136 and its surrounding cluster at 50 kpc even more severely. Because of its proximity to the Sun, the Orion molecular cloud, on the other hand, is one of the best studied star-forming regions in the Milky Way. At a distance of only 450 pc, the Orion nebula is sufficiently close to resolve the embedded population down to the sub-stellar regime (Muench et al. 2002). The extended molecular cloud hosts the young Orion Nebula Cluster (ONC) containing stars with ages between 0.3 and 1 Myr in its center. The Trapezium system, a dense cluster of massive stars, forms the core of the ONC. It is particularly interesting for the comparison with NGC 3603 and Arches that the ONC provided a spatially well-resolved testcase where mass segregation could be analysed quantitatively (Hillenbrand 1997). The Trapezium cluster is with a core density and mass of about one order of magnitude lower than NGC 3603 YC at the low-mass end of massive star-forming regions in the Milky Way (see Tab. 4), albeit an example of the mode of star formation we understand as normal in our local environment. As these star-forming regions play a major rôle in our

understanding of the stellar IMF, we wish to compare their characteristics in the context of the influence of the star-forming environment on cluster formation. Tab. 4 summarizes the known properties of these massive star-forming regions and their central clusters. Properties of the Antennae starburst clusters and Milky Way globular clusters are included for reference.

8.1. Comparison of cluster characteristics

8.1.1. NGC 3603

The extent of NGC 3603 YC is estimated to a radius of 4.4 pc by Nürnberger & Petr-Gotzens (2002), beyond which it becomes indistinguishable from the stellar field population. The core radius is estimated to 0.2 pc from a King-profile fit to the density profile (Grebel et al., private communication). Within a radius of ~ 1 pc, a total mass of $7000 M_{\odot}$ is derived via extrapolation of the observed MF down to $0.1 M_{\odot}$ from a combination of HST/WFPC2 core data and the ISAAC observations presented above (Stolte 2003). This estimate of the total cluster mass is a lower limit as it does not correct for the low-mass halo, which is difficult to quantify without independent field data. In the inner 0.12 pc ($d = 6$ kpc) of the dense cluster core, six O3 stars and three WN6 components are identified by Drissen et al. 1995.

8.1.2. R 136 and its surrounding cluster

As a consequence of the similarly compact central cluster and stellar mass content in the inner 1 pc, NGC 3603 was suggested to be “a clone of R 136” by Mof-

fat et al. 1994. Both clusters are with an age of 1-2 Myr equally young, and contain a massive O-star population in their centers. With $2 \times 10^4 M_{\odot}$ (Hunter et al. 1995), the total mass in stars in the cluster around R 136 is a factor of 2-3 larger than in NGC 3603 YC. With the given stellar mass content, the central 30 Dor cluster was very productive in forming high-mass stars. Within the inner 0.2 pc, six O3 stars are classified by Massey & Hunter (1998), comparable to the six O3 stars confined to the core of NGC 3603 YC ($r < 0.12$ pc). Despite this similarity in the immediate core, Massey & Hunter (1998) classify 65 stars spectroscopically with types earlier than B0 out to radii of 5.7 pc, of which 40 stars are of type O3, 4 are WN6 stars, 6 are in the O3/WN6 transition phase to Wolf-Rayet stars, and one O3-O3 binary is found, adding up to a total of 52 early O stars. In the 65 brightest stars with types B0 and earlier spectroscopically analyzed by Massey & Hunter, a strong bias to O3 stars is observed. A comparably large number of O3 stars is not known in any other local star-forming environment. Out of these, 21 O3 objects reside within 1 pc from R 136, while no more O3/WN6 sources except for the nine very early type stars in the innermost core of NGC 3603 YC are detected in the central 1 pc covered by the ISAAC data and further out to 4.2 pc (Moffat et al. 1994), the suggested cluster extent (Nürnberg & Petr-Gotzens 2002). In NGC 3603 YC, 84% (31) of the early O-star population ($M_V > -5.0$, $M \sim 25 M_{\odot}$) is confined to the innermost 0.5 pc, and all O-stars are found within 1.15 pc from the cluster center. A comparable number of 33 O and WN stars is classified by Massey

& Hunter (1998) in the inner 1.1 pc of the cluster surrounding R 136. However, this comprises only 63% of the 52 most luminous stars in the inner 30 Dor cluster down to the same M_V limit, while the remainder is spread out to radii as large as 4.2 pc (see Moffat et al. 1994, Fig. 9).

Comparable to the morphology observed in NGC 3603 YC, the cluster around R 136 displays a distinct dense cluster core surrounded by a stellar halo. The main difference between NGC 3603 YC and the core of 30 Dor is given by the spatial extent of the halo and its content of massive stars. While the dense cluster center around R 136 is with a radius of 4.7 pc (Hunter et al. 1995) comparable to the *total* cluster radius of 4.4 pc derived for NGC 3603 YC by Nürnberg & Petr-Gotzens (2002), a halo of young, massive stars with Wolf-Rayet characteristics is detectable out to a distance as far as 130 pc from R 136, beyond which it merges smoothly into the field population (Moffat et al. 1987). From the fact that only two more WNL stars are found in the rest of the LMC, Moffat et al. 1987 argue that the observed young population of WN6/7 stars are members of 30 Dor. If R 136 and 30 Dor were formed in a single starburst, this renders the halo around R 136 a factor of 30 larger than the radial extent of NGC 3603 YC.

8.1.3. Trapezium

The ONC contains $\sim 2000 M_{\odot}$ within a radius of 2.5 pc (Hillenbrand 1997). The ONC appears as an extended halo of low-mass stars around the dense central Trapezium cluster. The core radius in the cluster derived from King model

fitting is 0.2 pc (Hillenbrand & Hartmann 1998), identical to NGC 3603 YC. The central *stellar number* density inside the core is also very comparable, with $\rho_c = 1.7 \cdot 10^4 \text{ stars/pc}^3$ in the Trapezium core and $\rho_c = 1.4 \cdot 10^4 \text{ stars/pc}^3$ in NGC 3603 YC. There is, however, one significant difference between both clusters - the central mass density is with $\sim 10^5 M_\odot/\text{pc}^3$ (Moffat et al. 1994) in the starburst about one order of magnitude higher than the $2 \cdot 10^4 M_\odot/\text{pc}^3$ in the Trapezium core. Given the large number of at least 40 O-stars in NGC 3603 YC (Drissen et al. 1995), versus a mere ~ 10 OB stars in the ONC, the difference in mass density is not surprising. NGC 3603 YC contains the entire mass found in the ONC *only* within its core.

8.1.4. *Arches*

The Galactic Center Arches cluster falls with a total mass of $\sim 10^4 M_\odot$ and central density of $3 \cdot 10^5 M_\odot/\text{pc}^3$ inbetween NGC 3603 YC and the cluster surrounding R 136. As such, it is the most massive, young compact cluster in the Milky Way for which a detailed MF analysis is available. The core radius is estimated to be $\lesssim 0.24$ pc from the half-mass radius (Stolte 2003) comparable to both NGC 3603 YC and Trapezium, although the density profile cannot be used to derive a fitted core radius because it is heavily distorted by tidal disruption in the Galactic Center gravitational field. Due to the high stellar field density in the GC environment, the true extent and the population surrounding the cluster beyond a radius of 1 pc is currently not known. A part of the cluster popula-

tion has likely formed an extended tail or halo, as low- and intermediate-mass members are stripped off the cluster rapidly in the GC tidal field. Nevertheless, a compact, highly mass segregated high-mass core is observed in the center of a more extended intermediate-mass population, in structure comparable to NGC 3603 YC, but with a larger characteristic mass scale (Stolte et al. 2005; Stolte 2003).

8.2. MF slopes in four clusters

The central 4.7 pc of R 136/30 Dor exhibit a normal mass function with a slope of $\Gamma = -1.3 \pm 0.1$ in the mass range $15 < M < 120 M_\odot$, identical to the slope of a Salpeter IMF. The massive end, $30 < M < 120 M_\odot$, of this MF is obtained from spectroscopy of the high-mass population (Massey & Hunter 1998). In the MF derivation, the $120 M_\odot$ upper mass limit is imposed from the truncation of stellar evolution models. From luminosity and - where available - spectroscopy of the brightest, highest-mass stars, Massey & Hunter suggest initial masses of up to $150 M_\odot$. Given the total mass of the cluster, these authors argue that this is in agreement with an untruncated normal mass function up to the highest masses.

Hunter et al. (1996) study the radial variation in the MF slope in the mass range $2.8 < M < 15 M_\odot$ in four annuli with $0.11 < R < 1.1$ pc using HST/PC data. From inner to outer annuli, values of -1.0 ± 0.4 , -0.7 ± 0.4 , -1.1 ± 0.3 and -1.05 ± 0.2^5 , respectively, are derived, showing no variation with radius within

⁵cf. Massey & Hunter (1998) for corrections of the values given in Hunter et al. (1996)

the uncertainties. The same behaviour was derived in the case of NGC 3603 YC in Sec. 6. The HST/PC data analysed by Hunter et al. 1995 only resolve the cluster beyond 0.1 pc. Mass segregation in the form of a flattened MF slope is observed in NGC 3603 YC only inside the core radius of 0.2 pc (Sung & Bessell 2004), while segregation at larger radii is evidenced in the decrease in the mass fraction in high-mass stars (Sec. 7.2) and the truncation of the MF at the high-mass end (Sec. 6), but not in the slope of the MF. A mass segregated core biased to high-mass stars can thus not be entirely ruled out for R 136, although the HST/PC image presented in Massey & Hunter 1998 (see their Fig. 2) suggests that the center of R 136 is well resolved with HST, and the MFs in Hunter et al. 1996 do not show a depletion at the high-mass end as seen in NGC 3603 YC. The mass function slope of $\Gamma = -1.0$ to -1.1 ($2.8 < M < 15 M_{\odot}$) observed in approximately the same radial range, $0.1 < R < 1.1$ pc, agrees very well with the slope of $\Gamma = -0.9 \pm 0.1$ ($0.4 < M < 20 M_{\odot}$ in $0.2 < R < 1.0$ pc) in NGC 3603 YC, both subject to a similar saturation limitation at the massive end.

The mass function in the Trapezium system was investigated most recently by Muench et al. (2002). A slope of $\Gamma = -1.2 \pm 0.2$ is found for $0.6 < M < 5 M_{\odot}$, consistent with $\Gamma \sim -1.3$ found by Hillenbrand (1997) over a mass range $0.25 < M < 12 M_{\odot}$, the upper limit of the ONC IMF power law tail. These slopes are comparable to the overall slope in R 136 and its surrounding cluster ($2.8 < M < 120 M_{\odot}$, Massey & Hunter 1998) despite the different mass ranges covered, supporting the

idea of a universal power-law IMF above the turn-over mass. Again, no indication of a radially increasing slope is found outside the cluster core (Muench et al. 2002).

In the central parsec of the Arches cluster, the same slope of $\Gamma = -0.9 \pm 0.15$ as observed in NGC 3603 YC is obtained for the intermediate- to high-mass regime, $4 < M < 65 M_{\odot}$. The low-mass regime of the cluster is not yet resolved. Although all of the above slopes barely agree within the errors, the low fitting uncertainties probably underestimate the true slope uncertainty, as photometric age or distance uncertainties are not taken into account. Thus, there may be a weak indication of a flattened mass distribution in NGC 3603 YC and Arches, while the MFs in the clusters surrounding R 136 and the Trapezium follow a standard Salpeter law.

Although the spatial distribution of high-mass stars around R 136 differs drastically from the morphology observed in Trapezium, NGC 3603 YC and Arches, the slope of the mass function is almost identical. As already discussed in context of the radial variation and mass segregation in NGC 3603 YC, this supports the conclusion that the slope of the MF alone is not sufficient to understand mass segregation.

Given the diversity of the star-forming environments considered, the slopes of the present-day MFs are in remarkable agreement, in accordance with a universal IMF slope.

8.3. Primordial vs. dynamical segregation?

In all four clusters, a heavily mass segregated core is observed. Mass segregation in young clusters was shown for the ONC and

Trapezium in Hillenbrand 1997 (see also Hillenbrand & Hartman 1998). Hunter et al. 1995 conclude from dynamical considerations that the core inside R 136/30 Dor is entirely mass segregated for radii $r < 0.4$ pc, and their IMF suggests that at least 40% of the total mass are confined within this radius. We estimate a half-mass radius of 0.24 pc for Arches, thus about 50% of the mass are confined within the core, similarly indicated for NGC 3603 YC from the HST analysis (Stolte 2003; Sung & Bessell 2004). Do these heavily high-mass biased, mass segregated cores imply a preferential formation of high-mass stars in the cloud cores, and thus primordial segregation?

Although we are not in the position to give a final answer to this question, there are several indications we can derive from the comparison of the known clusters. In all four clusters, the present-day MF rapidly approaches a slope close to a standard IMF outside the core radius. In NGC 3603 YC we have seen that segregation mostly affects the high-mass stars, while the shape of the low-mass distribution appears constant with radius. A similar behaviour is observed in the form of a constant MF slope in the cluster around R 136 and Trapezium. In the Arches cluster the case is not clear due to the severe crowding and field contamination at masses below $\sim 4 M_{\odot}$. Despite these similarities in the intermediate-mass MF, NGC 3603 YC and 30 Dor show significant structural differences in the spatial distribution of high-mass stars. While both NGC 3603 YC and Trapezium exhibit a halo of low-mass objects, the cluster surrounding R 136 is the only local starburst

cluster that exhibits an extended halo of *high-mass* stars. Hunter et al. (1995) argue that the dynamical relaxation process is completed around R 136 in the innermost 0.4 pc, with the relaxation timescale for high-mass stars being much smaller than the cluster age within this radius. This situation resembles the derivations for NGC 3603 YC (Stolte 2003) and Orion (Hillenbrand & Hartmann 1998) in the respect that a short dynamical relaxation time prohibits one to distinguish primordial and dynamical segregation in the cluster center. In the extended halo surrounding R 136, however, the relaxation timescale is much larger due to the lower density and larger distance from the cluster center, such that stars formed in the outer regions of the cluster are not significantly segregated, but should still be found close to their birth positions. This implies that even the formation of the highest mass stars is *not* confined to the densest cluster region, as observed in the two Milky Way starburst clusters. Nevertheless, even the Milky Way hosts OB associations with lower stellar density capable of forming numerous O stars. The most prominent example discovered so far is the Cyg OB2 complex, which harbours 48 O stars with one star classified as early as O3 (Comerón et al. 2002, Hanson 2003). The young stellar population is extended over an area of ~ 20 pc \times 20 pc and lacks a compact core as opposed to the 1 pc into which the high-mass core of NGC 3603 YC is confined. Furthermore, populations hidden by extinction such as Westerlund 1 with an estimated core density of $\sim 10^5 M_{\odot} \text{pc}^{-3}$ are just recently unveiled by deep NIR observations. Westerlund 1 hosts at least 53 early-type stars and a total mass of $10^5 M_{\odot}$.

was suggested for the cluster (Clark et al. 2005), about one order of magnitude higher than estimated in NGC 3603 YC. Despite the comparable core density, O-type stars are found out to radii of 3 pc from the cluster center in Westerlund 1, and the spatial distribution of massive stars resembles the environment around R 136 more closely than NGC 3603 YC. In which respects is the star-forming environment in the LMC 30 Dor complex different from the NGC 3603 and Arches starburst environments?

Several differences are observed between 30 Doradus and the NGC 3603 molecular cloud. First of all, the total gas mass in the 30 Dor complex is with $(1.6) \cdot 10^7 M_{\odot}$ (Cohen et al. 1988, depending on the CO/H₂ conversion factor) at least one to two orders of magnitude larger than the $4 \cdot 10^5 M_{\odot}$ determined with the same method in NGC 3603 (Grabelsky et al. 1988). The lower metallicity in the LMC is frequently employed as the origin for differences in the young stellar population. However, the metallicity in 30 Dor has recently been shown to be 2/3 of the solar value (Peimbert 2003), such that significant changes in the outcome of the star-forming process are unlikely due to the marginally lower metallicity. Another significant difference was, however, suggested early: Werner et al. 1978 estimated an optical path length of 30 pc in 30 Dor vs. 0.1 pc in Orion from the much lower far-infrared optical depth, indicating a low density of dust and molecular material in the giant cloud. If photons travel longer distances, the heating of molecular cores may be much more efficient out to larger distances from the dense cloud

center, where the first high-mass stars are likely to have formed. The suggested optical path length is on the order of 100 times larger than in the Orion cloud. Taking into account the quadratically decreasing radiation field intensity with distance, one expects the spatial extent of clusters in Orion to be about one order of magnitude smaller than in 30 Dor, consistent with the 2.5 pc radius of the ONC. If the gas/dust distribution in NGC 3603 is similar to Orion, this could explain the ~ 30 times more extended halo of 130 pc around R 136 vs. 4.4 pc in NGC 3603. Observations of core temperatures in the 30 Dor complex as well as a comparative study of optical path lengths in Milky Way GMCs would clearly be very valuable to probe this suggestion.

A higher average cloud temperature is actually observed in the Galactic Center environment. Typical values of 70 K with a range of 30-200 K are measured in the GC (Morris & Serabyn 1996) vs. ~ 20 K observed in the cores of moderate star-forming environments. The intense radiation field in the GC may have a similar effect on core heating as the longer optical path length suggested for 30 Dor. As the path length in the GC is likely very small due to high gas and dust densities, the less efficient core cooling may locally cause the formation of cores with higher mass rather than extended formation of high-mass cores as in 30 Dor. A low cooling efficiency and intensive external heating may result in a higher core temperature when the opacity limit is reached and fragmentation ceases, implying a lower core density and thus higher mass needed for gravitational collapse. A lower critical

density at which fragmentation stops results in less fragmentation and a higher average core and final stellar mass according to recent numerical simulations (Jappsen et al. 2005). The present-day MF in the Arches cluster displays indications for a high-mass turn-over around $6 M_{\odot}$ followed by a possible depletion towards lower masses (Stolte et al. 2005). In contrast to 30 Dor, where high-mass stars form at large distances from the cluster center, but the overall IMF appears normal, an enhanced core temperature in the GC may have caused a locally top-heavy IMF in the Arches core.

The Arches cluster is known to be tidally disrupted rapidly by the strong GC tidal field. Thus, for this cluster a skewed present-day MF may well have resulted from dynamical segregation alone. In 30 Dor the spatial distribution of massive stars is unlikely to be caused by dynamical evolution, as the dynamical timescales in the outskirts of the cluster (beyond $r = 1$ pc) are larger than the cluster age (Hunter et al. 1995). Although NGC 3603 as a counterpart to the Arches cluster evolving in a moderate star-forming environment is estimated to be dynamically significantly mass segregated (see Sec. 7), and will likely not survive on globular cluster timescales due to its compactness, the dynamical timescales in NGC 3603 YC are still at least one order of magnitude longer than in the GC environment (Stolte 2003). Thus, the differences between Arches and NGC 3603 YC can be caused by dynamical evolution, while the structural discrepancies between NGC 3603 and the central 30 Dor cluster likely originate from intrinsic differences in the parental clouds.

Hillenbrand & Hartmann (1998) performed a detailed dynamical analysis of the ONC and its core, the Trapezium, and the mass segregation studied by Hillenbrand (1997). The radial variation in the mass distribution observed in NGC 3603 YC and the ONC is comparable despite the fact that the starburst cluster hosts at least 40 O-stars as opposed to only 3 O-stars in the Trapezium system. Hillenbrand & Hartmann derive cumulative mass distributions in different annuli for several mass bins. These CFs show a different shape for massive stars with $M > 5 M_{\odot}$, while the three mass bins between 0.3 and $5 M_{\odot}$ all show a remarkably identical behaviour. In the cluster core ($R < 0.5$ pc), however, all four mass intervals follow each other closely, indicating strong segregation in the core, producing a bias to massive stars with respect to the low-mass population. The similarity over the wide range in masses suggests a flat MF exclusively in the core of the ONC. At larger radii, mass segregation in the ONC is observed down to $1 - 2 M_{\odot}$, but not below these masses. This is surprisingly similar to NGC 3603 YC, where the CFs of the PMS population up to masses of $\sim 3 M_{\odot}$ are indistinguishable in different annuli, while for larger masses strong changes are observed (see Fig. 9).

From the central stellar density, the number of stars in the core, the mean density and the measured velocity dispersion of 2.5 km/s, Hillenbrand & Hartmann derive a relaxation time of 6.5 Myr in the ONC. This timescale is longer than the maximum age of ~ 1 Myr, suggesting that some amount of primordial segregation had to be present. The same authors

also note that if only the massive core with $\sim 400 M_{\odot}$ is taken into account, the higher mean mass and stellar density causes a decrease to $t_{relax} \sim 0.6$ Myr, comparable to the age of the young cluster population. This means that in the Trapezium, too, observational evidence for primordial segregation is weak, as the massive stars may have migrated to the cluster center within the lifetime of the cluster. Bonnell & Davies (1998) perform detailed N-body simulations of ONC-type clusters, and find that the mean mass in the core as well as the ratio of high- to low-mass stars can only be recovered if the massive stars are initially placed close to the core, in agreement with primordial segregation. Given the high stellar mass and density in the core of NGC 3603 YC, some amount of primordial segregation has likely contributed to shaping the cluster.

A weak indication for primordial segregation is given by the low-mass MF. Both the MF as well as the CFs in NGC 3603 YC and Trapezium (Hillenbrand & Hartmann 1998) display increasing truncation at the high-mass end with increasing cluster center distance, but the shape of the low-mass distribution remains remarkably constant. From purely dynamical segregation a systematic increase in low-mass stars with increasing radius and a corresponding decrease in the apparent median (and characteristic) mass is predicted. While measuring the radially varying characteristic mass in the form of the turn-over in the MF in NGC 3603 YC has to await higher resolution observations, the mass fraction in low-mass stars increases with radius in NGC 3603 YC as shown in Fig. 10 consistent with expectations from dynamical

evolution models. A detailed comparison with numerical simulations is needed to determine whether both the shape of the low- and high-mass MF as well as the increasing fraction of low-mass stars can be explained by dynamical segregation alone, or whether and how much primordial segregation is needed to reproduce the high-mass core along with the radially invariant properties observed in the low-mass halo.

In summary, although we cannot finally distinguish between primordial vs. dynamical segregation in the four clusters, we observed striking similarities between NGC 3603 YC and the ONC/Trapezium system, while structural differences are very prominent between NGC 3603 and the starburst surrounding R 136 in 30 Dor as well as the Arches cluster in the GC environment. From these we conclude that the star-forming environment, despite surprising similarities in the efficiency to produce the same relative fractions of high- and low-mass stars and thus the same IMF slope, influences the structural properties and thus the long-term survival of starburst clusters severely, and therefore also the potential emergence of globular clusters from starburst environments.

9. Summary and Conclusions

From high-resolution near-infrared photometry, the present-day MF in the Milky Way starburst cluster NGC 3603 YC is derived. Different treatments of the field star contamination, individual extinction correction, and binary estimates are used to obtain the MF. We show that the slope of the MF is surprisingly robust against the derivation procedure. A slope of -0.91 ± 0.15 is found in the mass range $0.4 <$

$M < 20 M_{\odot}$ for the integrated MF, in excellent agreement with the optically derived MF by Sung & Bessell 2004, who obtain the same slope in the mass range $1 < M < 100 M_{\odot}$ despite entirely different procedures employed to calculate the MF. This slope is identical to the slope found in the GC Arches starburst cluster, and only slightly flattened with respect to a Salpeter MF ($\Gamma = -1.35$).

Radial variations are observed in the spatial distribution of stars, especially reproduced in the fraction of high- to low-mass stars and thus the characteristic mass at a given radius, and the depletion of massive stars at the high-mass end of the MF. This radial variation is, however, not reproduced in the slope of the MF with values of -0.9, -1.1, -0.8, -0.9, -0.9 in five equal-area annuli from immediately outside the cluster core out to radii of 2 pc. Although the slope is frequently employed as the only parameter comparing the MFs in different star-forming environments, it may not be the most significant value to use. The fraction of low-mass stars, the characteristic mass and the upper mass limit reflect mass segregation more closely.

A detailed comparison between NGC 3603, 30 Dor/R 136 in the LMC, Orion/Trapezium, and the Galactic Center Arches cluster suggests that a mass segregated core with an extended stellar halo may be a common cluster structure in a diversity of environments. While the formation locus of the highest-mass stars appears confined to the cores of these two Milky Way starburst clusters, with the surrounding halo being comprised mainly of low-mass stars, stars as early as spectral type O3 seem capable of forming at large radial distances from

the cluster center around R 136 in 30 Dor. Interestingly, the morphology in the Galactic star-forming complex Cyg OB2 displays similarities to the cluster surrounding R 136, and it would be interesting to compare the cloud temperature and spatial distribution of stars in both regions. This suggests that the star-forming environment, although producing comparable MF slopes, shapes the structural appearance of young star clusters, and thus influences their long-term survival. While strong mass segregation is observed in the high-mass component of each cluster, and especially in the cluster core, the low-mass population appears constant in shape, decreasing only as expected from the density profile, over a large range of radii. This may indicate that some amount of primordial segregation had to be present in the clusters, even if dynamical segregation rapidly condensed the cluster core even more. Detailed N-body simulations adjusted to the derived cluster characteristics as were performed for the Trapezium cluster by Bonnell & Davies (1998) are required to distinguish primordial and dynamical segregation in NGC 3603 YC.

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Fig. 1.— K_s 39 min ISAAC image ($3'4 \times 3'4$, North is up, East left). The selection of the main cluster center, $R < 33''$ (outer circle), as suggested by enhanced stellar density, and of the field population to the East of the cluster (white boxed area) are shown. Circles mark radial annuli with $7''$, $20''$, $27''$, and $33''$.

Fig. 2.— Density profile of NGC 3603 YC. The dotted line indicates the limit where field star contamination exceeds 10%.

Fig. 3.— Recovery fractions from artificial star tests.

The recovery rates are shown for the cluster center and field including the polynomial fits used in the field star fraction and mass function incompleteness correction (left). The radial variation in the completeness due to varying stellar density is compared for the different annuli (right) for which the MF is calculated. Variations are significant only in the innermost annulus ($7'' < R < 20''$). The huge loss of stars in the innermost $7''$ reflects the saturation and crowding problems in the cluster core, which is excluded from the MF derivation.

Fig. 4.— Color-magnitude diagram of the inner $33''$ of NGC 3603 YC.

The unsubtracted cluster population is shown in the left panel, the observed field star population (not yet scaled to the same area) in the middle, and the subtracted cluster population used for mass function derivations in the right panel. Field stars were statistically subtracted in color-magnitude bins of 0.5×0.5 mag. The 50% completeness limit down to which mass functions are fitted is indicated as a dashed line. Note that the magnitude corresponding to 50% completeness varies with radial distance from the cluster center.

Fig. 5.— Selection of stars around the average MS (left) and PMS (right) isochrone.

Stars with colors up to 0.25 mag blueward of the PMS and MS isochrones are included, and redward up to 0.35 mag in the case of MS stars and 0.5 mag in the case of PMS stars. The selected stars represent a typical sample used for the MF derivation (after field subtraction).

Fig. 6.— Mass function of NGC 3603 YC.

All MFs are derived from the combined MS and PMS population (Fig. 5) for an age of 1 Myr, distance modulus of 13.9 mag and foreground extinction of $A_V = 4.5$ mag (PMS) and $A_V = 4$ mag (MS). Dashed lines are individual fits for the PMS ($0.4 < M/M_\odot < 4$) and MS ($4 < M/M_\odot < 20$), and the solid red line is the combined MF fit. Top panel: MF calculated from simple star counts. Middle panel: MF calculated after field subtraction and individual dereddening. Bottom panel: Mass function derived including binary correction. Stars on the binary candidate sequence were shifted down by $\Delta J_s = +0.75$ mag, and 30% of the PMS stars selected randomly were treated in the same way. One equal-mass companion was included for each binary candidate.

The similarity in the combined MF slope is striking despite the different procedures used.

Fig. 7.— Radial variation in the combined mass function.

Three consecutive annuli with identical area coverage are chosen. In the combined MF a reasonable fit could be performed in the two inner annuli up to $16 M_{\odot}$, while in the outermost annulus only the PMS contributes significantly to the stellar population, such that the fit proceeds only from 0.4 to $4 M_{\odot}$. Despite the observed decrease in the number of high-mass stars in the outer annuli, no clear steepening in the MF in the form of a steeper slope Γ reflects the depletion of high-mass stars at large radii.

Fig. 8.— Cumulative mass distributions of NGC 3603 YC.

The CF for the cluster selection $7'' < R < 33''$ is shown in the upper left panel. Theoretical mass distributions are overlaid (dashed lines) with slopes of $-0.3 > \Gamma > -1.3$ in steps of 0.2 , the latter corresponding to the Salpeter slope (solid line). All CFs are normalised to unity at $M = 0.4 M_{\odot}$, and the absolute number of stars entering each CF is given in the upper right corner. The radial CFs are displayed in the subsequent panels, with annuli indicated in the upper right corner. In each radial CF, the cluster CF from the first panel is also shown for comparison. The two outer annuli extending to $65''$ indicate that the pre-main sequence population ($M < 4 M_{\odot}$) is not truncated even at large radii, while the main sequence population is strongly concentrated towards the cluster center.

Fig. 9.— Radial cumulative mass distributions of NGC 3603 YC.

This comparison between radial CFs of all annuli shows - in contrast to the binning-limited MF - a clear trend towards decreasing values of Γ with increasing radius in the inner three annuli. Beyond $33''$, the increase at the high-mass end is most probably due to incomplete field subtraction. On the low-mass end, however, the mass distribution corresponds very well to the cluster pre-main sequence distribution. Indeed, between all 5 annuli, no deviation in the distribution can be detected below $3 M_{\odot}$ except for a slight flattening in the cluster center (top curve). At masses above $3 M_{\odot}$, a strong decrease in the relative fraction of high-mass stars is observed, confirming the mass segregation observed in the MFs.

Fig. 10.— Fraction of high- to low-mass stars vs. radius.

The left panel shows the radial change in the number ratio of stars with $M \geq 4 M_{\odot}$ to stars with $1 M_{\odot} < M < 4 M_{\odot}$ (left). Large symbols represent the five radial annuli used to study MF variations, including individual incompleteness corrections for each annulus. The MS/PMS transition is chosen as mass limit between the high- and the low-mass population, as these two populations are known to be physically different, such that the ratio simultaneously reveals the radial change in the number of MS vs. PMS stars. The strong decrease in the fraction of high-mass stars reflects the segregation of massive stars towards the cluster center. The right panel shows the radial variation in the mass fraction for the same criteria.

Table 1: Fraction of stars on binary candidate sequence. Only MS stars are selected.

J_s mag	N_{binary}	N_{single}	$N_{binary}/(N_{single} + N_{binary})$
12 - 13 mag	9	19	0.32
13 - 14 mag	12	38	0.24
14 - 14.8 mag	15	42	0.27
all	36	99	0.28

Table 2: Mass Function derivations for NGC 3603 YC.

Model number and description	PMS + MS fit	PMS fit	MS fit
no field subtraction, no dereddening	$\Gamma = -0.91 \pm 0.10$	$\Gamma = -0.78 \pm 0.32$	$\Gamma = -0.75 \pm 0.20$
with field subtraction, no deredding	$\Gamma = -0.87 \pm 0.10$	$\Gamma = -0.72 \pm 0.33$	$\Gamma = -0.72 \pm 0.25$
with dereddening, no field subtraction	$\Gamma = -0.91 \pm 0.10$	$\Gamma = -0.85 \pm 0.30$	$\Gamma = -0.56 \pm 0.20$
with dereddening and field subtraction	$\Gamma = -0.85 \pm 0.10$	$\Gamma = -0.73 \pm 0.32$	$\Gamma = -0.57 \pm 0.20$
binary candidates rejected	$\Gamma = -0.97 \pm 0.10$	$\Gamma = -0.73 \pm 0.33$	$\Gamma = -0.91 \pm 0.12$
visible binary sequence corrected (MS and transition)	$\Gamma = -1.00 \pm 0.10$	$\Gamma = -0.73 \pm 0.33$	$\Gamma = -0.95 \pm 0.22$
visible binary seq. and statistical PMS correction 30%	$\Gamma = -0.91 \pm 0.08$	$\Gamma = -0.67 \pm 0.26$	$\Gamma = -0.84 \pm 0.13$
2 Myr MS, all corrections	$\Gamma = -0.91 \pm 0.08$	$\Gamma = -0.61 \pm 0.21$	$\Gamma = -1.03 \pm 0.23$
3 Myr MS, all corrections (fit $< 15 M_{\odot}$)	$\Gamma = -0.84 \pm 0.09$	$\Gamma = -0.64 \pm 0.22$	$\Gamma = -0.75 \pm 0.10$

Table 3: Radial variation of the mass function.

annulus	PMS + MS fit	remark
$7'' < R < 20''$	$\Gamma = -0.89 \pm 0.14$	MS + PMS fit
$20'' < R < 27''$	$\Gamma = -1.09 \pm 0.15$	MS + PMS fit
$27'' < R < 33''$	$\Gamma = -0.76 \pm 0.21$	PMS fit only
$33'' < R < 46''$	$\Gamma = -0.99 \pm 0.26$	PMS fit only
$46'' < R < 65''$	$\Gamma = -0.85 \pm 0.23$	PMS fit only

Table 4: Comparison of young, massive clusters.

cluster	M_{total} M_{\odot}	extent pc	r_{core} pc	ρ_{core} $M_{\odot} \text{ pc}^{-3}$	age Myr	MF slope Γ	ref
Arches	10^4	1 (?)	0.2	$3 \cdot 10^5$	2 – 3	-0.9 ± 0.15	3, 4
NGC 3603 YC	$> 7 \cdot 10^3$	4.4	0.2	10^5	1 – 3	-0.9 ± 0.1	4
R 136	$2 \cdot 10^4$	4.7	0.02	$5 \cdot 10^4$	1 – 5	-1.3 ± 0.1	1
Orion	10^3	3	0.2	$4 \cdot 10^4$	0.3 – 1	-1.2 ± 0.1	2
Antennae starbursts	$10^4 - 10^6$	1 – 10	?	10^3	1 – 20	?	5
Milky Way GCs	10^4 - few 10^5	few pc	≈ 1	$10^2 - 10^6$	10 Gyr	-1.3	various

1 - Massey & Hunter (1998); 2 - Hillenbrand & Hartmann (1998); 3 - Figer et al. (1999); 4 - Stolte 2003; 5 - Whitmore et al. (1999). Average Milky Way globular cluster parameters compiled from various sources.

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